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Microstructure and some mechanical properties of fly ash particulate reinforced AA6061 aluminum alloy composites prepared by compocasting

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ABSTRACT

Fly ash has gathered widespread attention as a potential reinforcement for aluminum matrix composites (AMCs) to enhance the properties and reduce the cost of production. Aluminum alloy AA6061 reinforced with various amounts (0, 4, 8 and 12 wt.%) of fly ash particles were prepared by compocasting method. Fly ash particles were incorporated into the semi solid aluminum melt. X-ray diffraction patterns of the prepared AMCs revealed the presence of fly ash particles without the formation of any other intermetallic compounds. The microstructures of the AMCs were analyzed using scanning electron microscopy. The AMCs were characterized with the homogeneous dispersion of fly ash particles having clear interface and good bonding to the aluminum matrix. The incorporation of fly ash particles improved the microhardness and ultimate tensile strength (UTS) of the AMCs.

1. Introduction

The conventional aluminum alloys do not always provide the required properties under all service conditions which are overcome by reinforcing those alloys with ceramic particles. Such reinforced aluminum alloys are universally known as aluminum matrix composites (AMCs). AMCs have received considerable attention in the present material world owing to their high strength, stiffness and high wear resistance compared to unreinforced alloys [1–3]. One essential factor which limits the application of AMCs is the high cost of fabrication which can be minimized by using inexpensive reinforcements such as fly ash and natural minerals. Fly ash is a waste by-product of coal combustion in thermal power plants which is available in large quantities in the Indian subcontinent and all over the world [4,5]. Fly ash is cheaper compared to other traditional reinforcements such as SiC, Al_2O_3, B_4C and TiC.

Various conventional methods and specific patented methods have been used to fabricate AMCs reinforced with different kinds of ceramic particles which include but not limited to powder metallurgy [6], mechanical alloying [7], stir casting [8], squeeze casting [9], compocasting [10] and spray deposition [11]. The processing method influences the mechanical and the tribological behavior of the AMCs. Enhancement of AMC properties requires the successful incorporation of ceramic particles into the aluminum matrix and obtaining good bonding between them. The above listed processing methods can be categorized into solid state processing and liquid state processing. Liquid method of processing is preferred because of its simplicity, ease of adoption and applicability to mass production [12].

Stir casting is the widely used liquid method of processing to prepare AMCs where the aluminum matrix is completely melted and ceramic particles are added into the molten metal in a vortex created using a mechanical stirrer [13]. The major setback in stir casting is the wettability between the molten aluminum matrix and the ceramic particle. Various methods have been attempted by researchers to improve wettability which includes adding wettability agents [14] and fluxes [15], preheating the ceramic particle [16] and coating the ceramic particle [17]. Those techniques increase the cost of fabrication. Another economical method to improve the wettability is to reduce the casting temperature and add the ceramic particles when the aluminum is in a semi solid state. This modified stir casting method is known as compocasting or slurry casting [10]. Several investigators reported enhanced wettability and better distribution of ceramic particles in the AMCs produced using compocasting compared to stir casting [18–20].

Some studies on aluminum alloys reinforced fly ash particulate composites were reported in the literatures [21–30]. Ramachandra and Radhakrishna [21] synthesized LM25/fly ash AMC by stir casting method and reported an appreciable enhancement in the mechanical and wear properties of the AMC. Wu et al. [22] prepared AA6061/fly ash AMC by squeeze casting method and measured the damping capacity of the AMC using the forced mode and the bending-vibration mode on a multifunctional internal friction apparatus. Rajan et al. [23] produced A356/fly ash AMC by various

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casting routes and assessed the effectiveness of stir casting, compocasting and squeeze casting on the distribution of fly ash particles in the AMC. Sudarshan and Surappa [24] fabricated A356/fly ash AMC using stir casting followed by hot extrusion and analyzed the effect of fly ash particulate size on the microstructure and mechanical properties of the AMC. Kumar et al. [25] developed AA6061/fly ash AMC by powder metallurgy method and carried out extensive microstructural characterization of the AMC. Rao et al. [26] made AA2024/fly ash AMC by stir casting method and obtained enhanced pitting corrosion behavior of the AMC. Itskos et al. [27] synthesized A356/high-Ca lignite fly ash AMC by pressure infiltration technique and correlated the microstructure to the mechanical and wear properties of the AMC. Murthy et al. [28] produced AA2024/fly ash nano AMC by ultrasonic cavitation method and evaluated the microstructure and tensile strength of the AMC. Marin et al. [29] prepared Al/fly ash AMC by powder metallurgy method and investigated the electrochemical behavior of the AMC. He proposed various mechanisms for the electrochemical behavior of the AMC. Uju and Oguocha [30] fabricated A535l/fly ash AMC by stir casting method and estimated the coefficient of thermal expansion of the AMC experimentally as well as using micromechanical models.

In this work, an attempt is made to fabricate aluminum alloy AA6061 reinforced with fly ash particles by compocasting method and study the effect of fly ash content on microstructure and mechanical properties of AA6061/fly ash AMCs.

2. Experimental procedure

AA6061 rods were placed in a graphite crucible which was coated inside to avoid contamination and heated using an electrical furnace. The chemical composition of AA6061 aluminum alloy and fly ash particles are respectively presented in Tables 1 and 2. The fly ash particles were collected from Thermal Power Station, Tuticorin, India. The SEM micrograph and XRD pattern of the fly ash particles are shown in Fig. 1. Most of the fly ash particles exhibited solid spherical shape and precipitator type fly ash. The density and average size of fly ash particles were 2300 kg/m^3 and 1–2 µm respectively. The temperature of the furnace was maintained at 610 °C. Measured quantity of fly ash particles was added to the semi solid aluminum alloy. Simultaneous stirring of the semi solid aluminum alloy was carried out using a mechanical stirrer driven by an electric motor. Stirring was continued till all the fly ash particles were added to the semi solid aluminum alloy. The semi solid composite melt was then poured into a permanent die at room temperature. The pouring temperature was kept slightly higher

Table 1
Chemical composition of AA6061 aluminum alloy.

Element	Mg	Si	Fe	Mn	Cu	Cr	Zn	Ni	Ti	Aluminum
wt.%	0.95	0.54	0.22	0.13	0.17	0.09	0.08	0.02	0.01	Balance

Table 2
Chemical composition of fly ash.

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MnO_2	K_2O	TiO_2	Na_2O	Others
wt.%	49.50	25.54	8.92	6.13	1.03	0.65	0.53	0.47	Balance

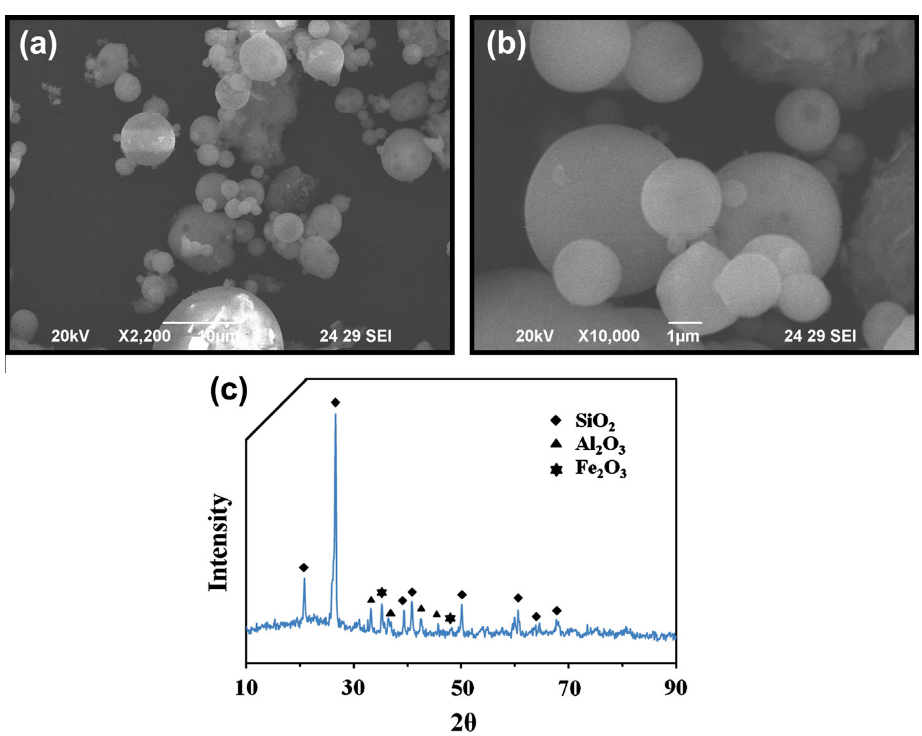

Fig. 1. (a) Lower and (b) higher magnification SEM micrographs of fly ash particles and (c) XRD pattern of fly ash particles.

than the casting temperature to enhance fluidity. Castings were taken with various amounts of (0, 4, 8 and 12 wt.%) of fly ash particles. The casting facility which was used to fabricate the composites is shown in Fig. 2.

Fig. 2. Casting facility used to prepare AA6061/fly ash AMCs.

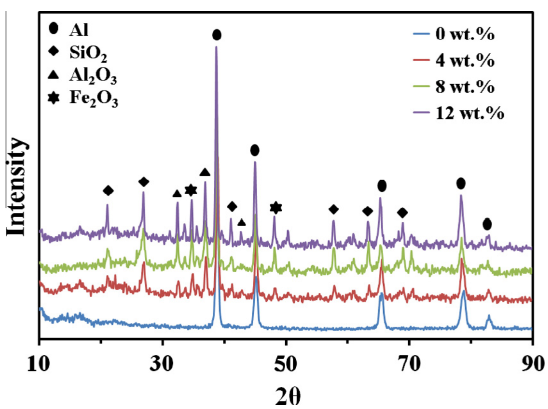

Fig. 3. XRD patterns of AA6061/fly ash compocast composites.

Specimens were prepared from the castings to carry out microstructural and mechanical characterization. The specimens were polished using standard metallographic technique and etched with Keller's reagent. The etched specimens were observed using an optical microscope and a scanning electron microscope (SEM). X-ray diffraction patterns (XRD) were recorded using Panalytical X-ray diffractometer. The microhardness was measured using a microhardness tester at 500 g load applied for 15 s. The tensile specimens were prepared as per ASTM: E8M-11 standard having a gauge length of 40 mm, a gauge width of 7 mm and a thickness of 6 mm. The ultimate tensile strength (UTS) was estimated using a computerized universal testing machine. The fracture surfaces of the failed tensile specimens were observed using SEM.

3. Results and discussion

Aluminum alloy AA6061 reinforced fly ash particulate composites were successfully fabricated using compocasting. The metallurgical and mechanical characterization of the fabricated AA6061/fly ash AMCs are discussed below.

3.1. X-ray diffraction analysis of AA6061/fly ash AMCs

The XRD patterns of the prepared composites are presented in Fig. 3. The diffraction peaks of SiO_2, Al_2O_3 and Fe_2O_3 which presents the major composition of fly ash particles are distinctly seen. The intensity of those peaks increases as fly ash content is increased. It is observed in Fig. 3 that the aluminum diffraction peaks in the composites are slightly shifted to lower 2θ compared to that of aluminum alloy due to the incorporation of fly ash particles in the aluminum matrix. It is evident from Fig. 3 that diffraction peaks of any other elements except Al, SiO_2, Al_2O_3 and Fe_2O_3 are not detected. This observation leads to a conclusion that the integrity of fly ash particles is preserved during casting. Fly ash particles are thermodynamically stable at the applied casting temperature.

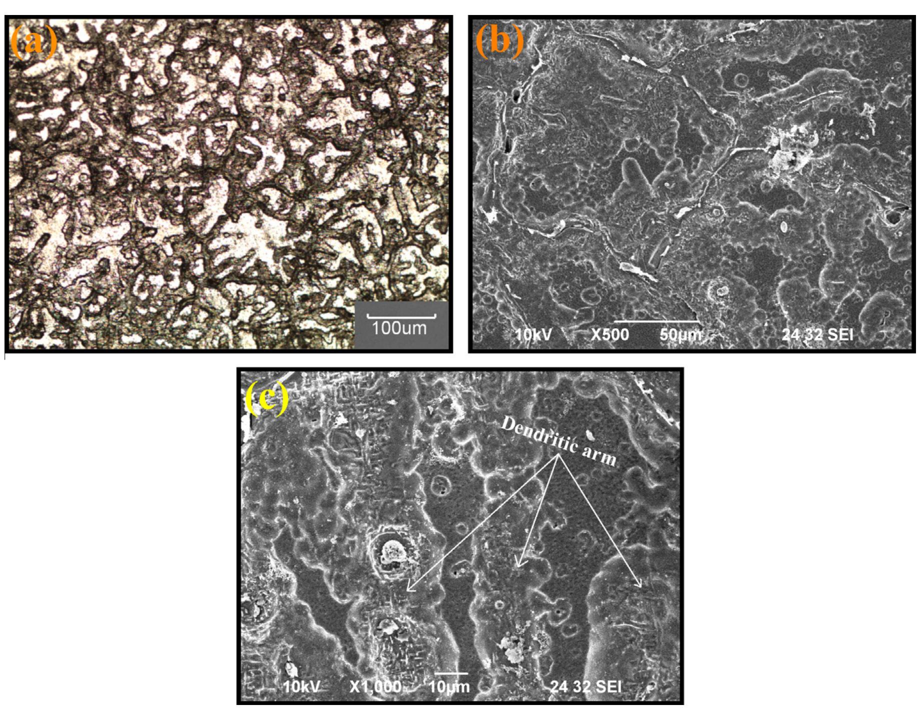

Fig. 4. (a) Optical photomicrograph, (b) and (c) SEM micrographs of cast AA6061 alloy.

There is no interfacial reaction between fly ash particles and aluminum matrix during casting. Such interfacial reactions would often result in the formation of brittle intermetallic compounds in the composite and degrade the mechanical and tribological properties. Rajan et al. [23] reported a wider interfacial reaction zone and the formation of $MgAl_2O_4$ spinal at the fly ash–aluminum interface in the A356/fly ash AMC produced by stir casting. Zahi and Daud [5] noticed iron rich intermetallic compounds in the Al/fly ash AMC prepared using stir casting. The absence of those intermetallic compounds in the XRD patterns of the prepared composites can be attributed to the processing temperature of compocasting. The processing temperature of compocasting is considerably low compared to stir casting which is insufficient to initiate interfacial reactions. Compocasting route to fabricate AMCs helps to suppress the interfacial reactions.

3.2. Microstructure of AA6061/fly ash AMCs

The optical and SEM photomicrographs of the cast aluminum alloy AA6061 and the prepared AA6061/fly ash AMCs are respectively shown in Figs. 4 and 5. The optical and SEM photomicrographs of as cast AA6061 are revealed in Fig. 4. The microstructure depicts the dendritic structure caused by solidification. The high rate of cooling known as super cooling during solidification forms such a dendritic structure. The dendritic structure consists of elongated primary α-Al dendritic arms having a high aspect ratio. The alloying elements of AA6061 such as Mg and Si are noted to be higher than that of their solubility limit. As a result the intermetallic phase Mg_2Si is formed around the dendrites during casting.

The SEM micrographs of the prepared AA6061/fly ash AMCs are presented in Fig. 5. The common casting defects such as porosity, shrinkages or slag inclusion are not visible in the micrographs which demonstrate the quality of castings. It is evident from the figure that the incorporation of fly ash particles refined the dendritic structure of the matrix alloy. Fly ash particles influence the solidification pattern of the semi solid composite melt which resulted in the refinement of grains. The grain refinement occurs due the following two factors. The incorporation of fly ash particles offers resistance to the growing α-Al grains during the solidification process. Fly ash particles act as a grain nucleation site and the aluminum grains solidify on it. When the content of fly ash particles increases, number of nucleation sites is created owing to constitutional under cooling zone in front of the particles. The net result is more grain refinement forming finer grains.

It can be seen from Fig. 5 that most of the fly ash particles are located in intra granular regions. Intra granular distribution of ceramic particles is preferred over inter granular distribution in AMCs to obtain higher mechanical and tribological properties.

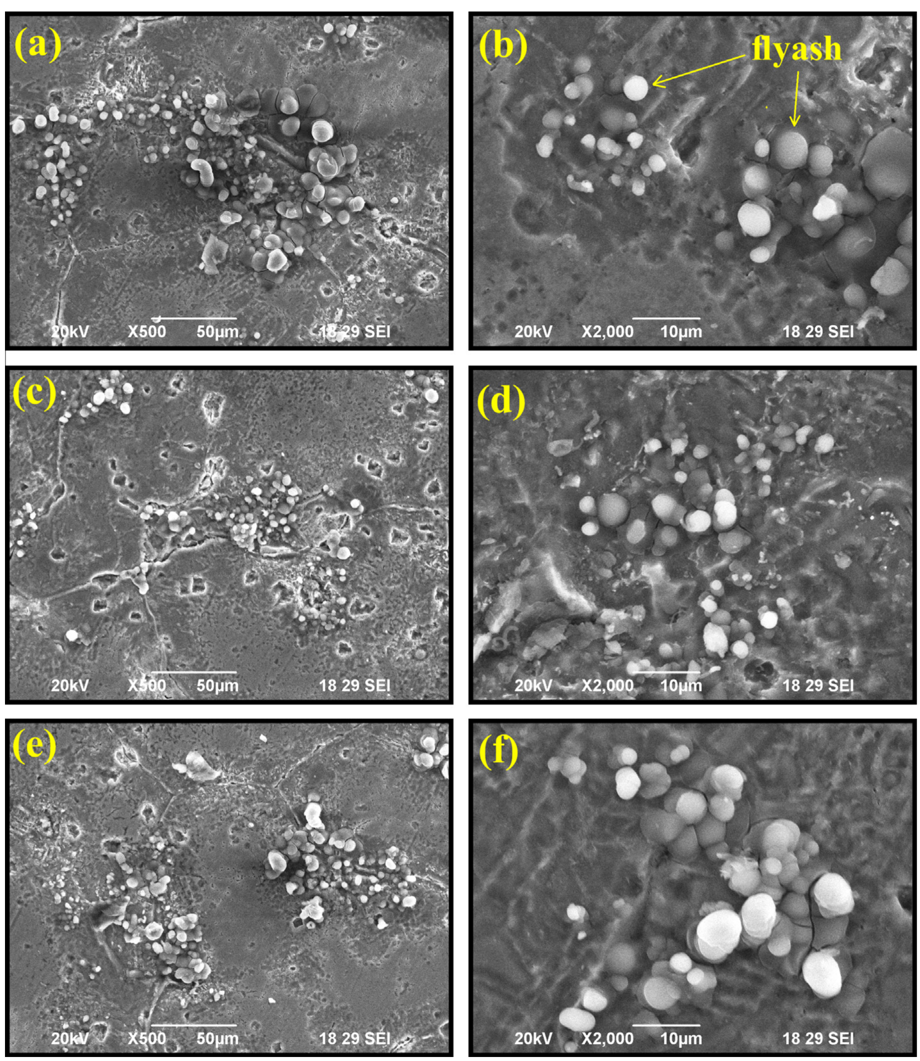

Fig. 5. SEM micrographs of AA6061/fly ash compocast composites containing fly ash; (a) 4 wt.%, (b) 4 wt.%, (c) 8 wt.%, (d) 8 wt.%, (e) 12 wt.% and (f) 8 wt.%.

The distribution of fly ash particles in the semi solid composite melt is influenced by several factors such as convection current, movement of the solidification front against particles and buoyant motion of particles [31]. The velocity of the solidification front plays a crucial role to achieve intra or inter granular particle distribution. When the velocity of the solidification front is above a critical velocity, the solidification front grows around the particles and engulfs them leading to intra granular distribution and vice versa. The critical velocity is affected by the particle size and the temperature gradient. Observing the intra granular distribution of fly ash particles, it appears that the particles are engulfed by the solidification front.

It is further evident from Fig. 5 that the fly ash particles are dispersed nearly homogeneously in the aluminum matrix. Such kind of particulate dispersion is an essential requirement to obtain higher mechanical properties of the AMCs. The solidification process governs the distribution of fly ash particles in the aluminum matrix. The density variation between the aluminum matrix and the fly ash particle play a critical role during solidification. When the density of ceramic particle is higher compared to aluminum matrix, it begins to sink in the melt and vice versa. Suspension of ceramic particles in the melt for a long time is necessary to obtain a homogenous dispersion. Since compocasting is a semi solid melt process, the tendency of particles to sink or float is retarded. The movement of particles within the semi solid aluminum alloy after stirring is minimum compared to stir casting due to enhanced viscosity of the composite slurry [32]. The other factors which help to resist the free movement of fly ash particles are; (i) little density variation between aluminum alloy and fly ash particle which causes the particles neither to float nor to sink and (ii) the wetting action between semi solid aluminum and fly ash particles. Thus, a fairly homogenous dispersion of fly ash particles in the aluminum matrix is obtained.

The SEM micrographs of AA6061/12 wt.% fly ash AMC at higher magnification is shown in Fig. 6. The figure reveals the finer details of the interface between the aluminum matrix and fly ash particles. A clear interface exists between aluminum matrix and fly ash particles. No reaction products surround the fly ash particle. It is evident from the figure that there is no interfacial reaction between aluminum and fly ash. It is reported by others that when interfacial reaction takes place between aluminum and ceramic particles, the reaction products always surrounds the particle and deteriorate the interfacial strength [23,33]. A pure interface is required to enhance the load bearing capacity of the AMC. It is also observed from the figure that the fly ash particles are well bonded to the aluminum matrix. Neither voids or pores nor discontinuities or micro cracks are seen around the particles. It should be noted that no wettability agents such as magnesium was added in this work. Incorporation of fly ash particles into the semi solid aluminum alloy improves the wettability.

3.3. Mechanical properties of AA6061/fly ash AMCs

The effect of weight percentage of fly ash particles on micro hardness and UTS of AA6061/fly ash AMCs is respectively presented in Figs. 7 and 8. It is evident from these figures that the incorporation of fly ash particles significantly enhances the micro hardness and UTS. AA6061/12 wt.% fly ash AMC exhibits 132.21% higher microhardness and 56.95% higher UTS compared to unreinforced AA6061 alloy. The strengthening of AA6061 by the incorporation of fly ash particles can be explained as follows. Aluminum alloy AA6061 and fly ash have different thermal expansion coefficients. During the solidification of the composite, strain fields are created around fly ash particles because of the difference in the thermal expansion coefficients. The strain fields piles up dislocations. The interaction between dislocations and fly ash particles offer resistance to the propagation of cracks during tensile loading. The grain refinement provided by the fly ash particles presents more area to resist the load. The clear interface and good bonding of fly ash particles retards the detachment of particles from the aluminum matrix. The uniform distribution of fly ash particles provides Orowan strengthening [34]. Therefore, the microhardness and UTS of AMC are enhanced by fly ash particles. More the weight percentage of fly ash, more will be the effect of the above discussed factors which further increases the mechanical properties. The elongation of the AMCs decreases as shown in Fig. 8b when the weight percentage of fly ash particles is increased. Similar results were reported by Ramachandra and Radhakrishna [21]. The grain refinement and reduction of ductile matrix content when the weight percentage of fly ash particles is increased reduce the ductility of the AMCs.

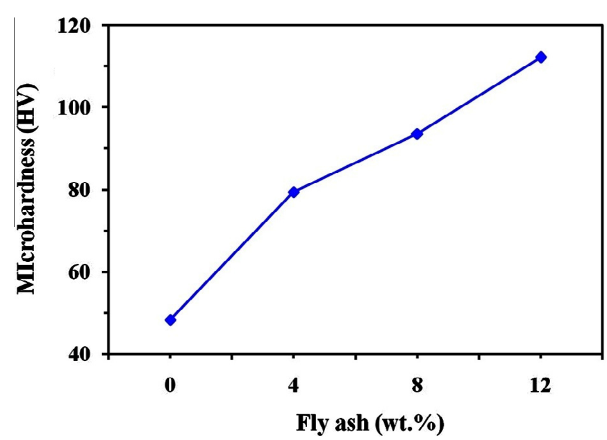

Fig. 7. Effect of fly ash content on microhardness of AA6061/fly ash compocast composites.

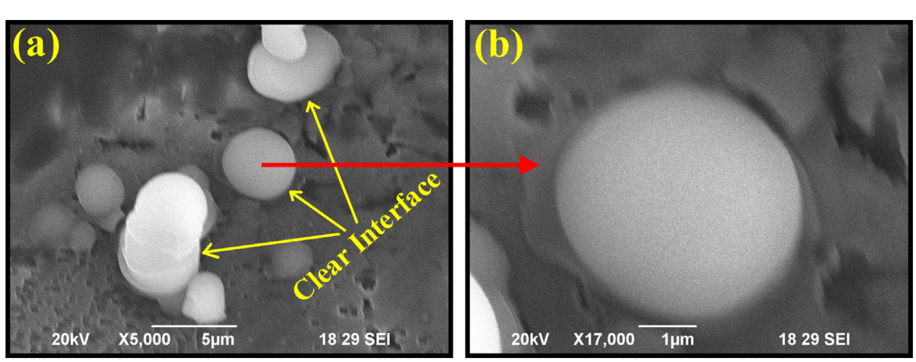

Fig. 6. (a) and (b) SEM micrographs of AA6061/fly ash compocast composites at higher magnification.

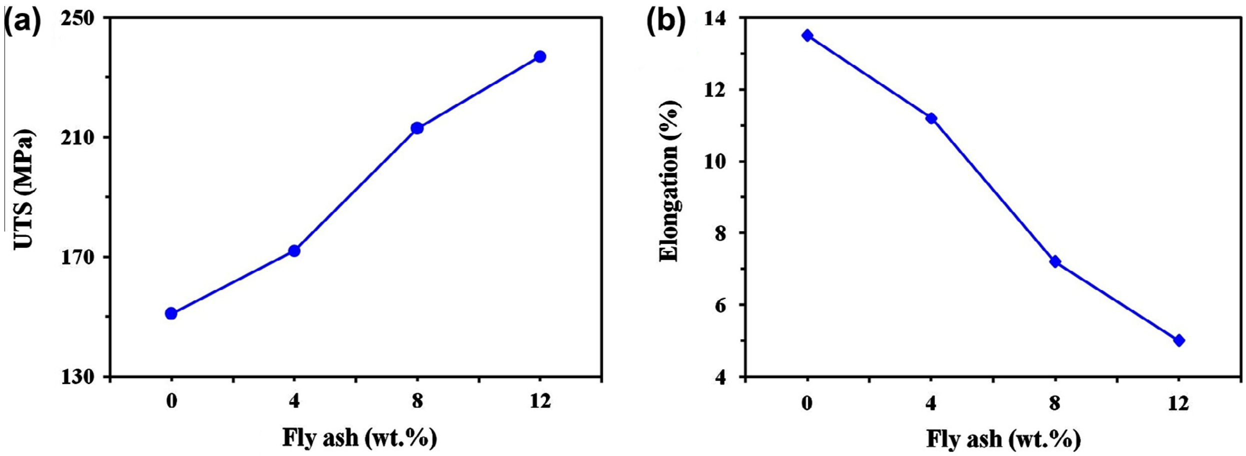

Fig. 8. Effect of fly ash content on: (a) tensile strength and (b) elongation of AA6061/fly ash compocast composites.

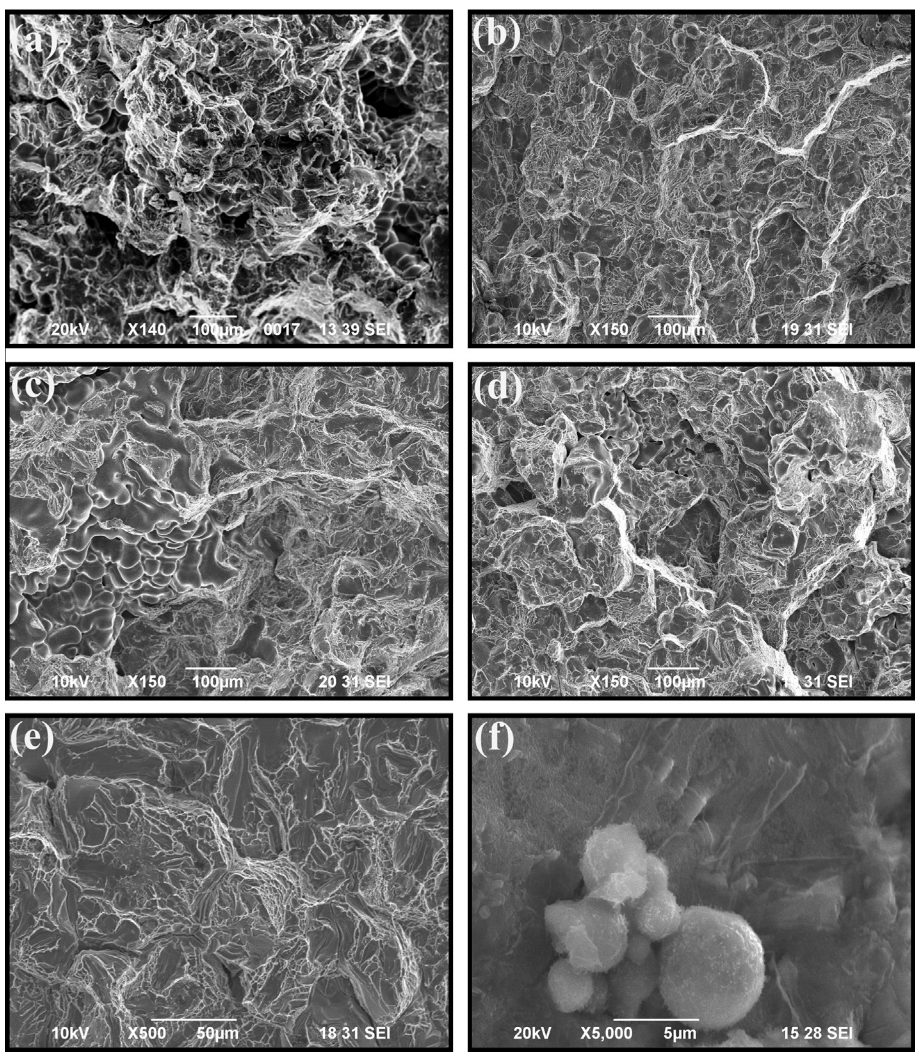

Fig. 9. Fracture morphology of AA6061/fly ash compocast composites containing fly ash: (a) 0 wt.%, (b) 4 wt.%, (c) 8 wt.%, (d–f) 12 wt.%.

The fracture morphology of the tensile tested specimens of AA6061/fly ash AMCs is shown in Fig. 9 which presents the effect of weight percentage of fly ash particles. The fracture morphology of the matrix alloy AA6061 in Fig. 9a shows bigger and uniformly distributed voids which indicate a ductile fracture. The fracture morphology of the prepared AA6061/fly ash AMCs (Fig. 9b–d) show smaller size voids compared to that of the matrix alloy which indicate macroscopically brittle fracture and microscopically ductile fracture. The incorporation of fly ash particles refined the grain size of aluminum alloy and reduced the ductility which resulted in smaller size voids. The fracture morphology of AA6061/12 wt.% fly ash AMC at higher magnification is shown in Fig. 9e and f. The ductile shear bands in the fracture morphology (Fig. 9e) indicate that some amount of ductility is retained by the AMC. Fly ash particles remain intact in many places (Fig. 9f) which gives evidence to the existence of good interfacial bonding between the aluminum matrix and fly ash particles.

4. Conclusions

AA6061/fly ash AMCs were successfully fabricated using compocasting method. There was no formation of any intermetallic compounds due to interfacial reaction. The fly ash particles were thermodynamically stable at the compocasting temperature. The majority of the fly ash particles were located in intra granular regions. The fly ash particles were dispersed homogeneously in the AMCs. The interface between the aluminum matrix and fly ash particle was clear and the bonding was proper. The incorporation of fly ash particles into semi solid aluminum alloy improved the wettability. The addition of fly ash particles enhanced the microhardness and tensile strength of the AMCs. AA6061/12 wt.% fly ash AMC exhibited 132.21% higher microhardness and 56.95% higher UTS compared to unreinforced AA6061 alloy.

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